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Ignition and Inertial Confinement Fusion at The National Ignition Facility

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Abstract. The National Ignition Facility (NIF), the world's largest and most powerful laser system for inertial confinement fusion (ICF) and for studying high-energy-density (HED) science, is now operational at Lawrence Livermore National Laboratory (LLNL). The NIF is now conducting experiments to commission the laser drive, the hohlraum and the capsule and to develop the infrastructure needed to begin the first ignition experiments in FY 2010. Demonstration of ignition and thermonuclear burn in the laboratory is a major NIF goal. NIF will achieve this by concentrating the energy from the 192 beams into a mm³-sized target and igniting a deuterium-tritium mix, liberating more energy than is required to initiate the fusion reaction. NIF's ignition program is a national effort managed via the National Ignition Campaign (NIC). The NIC has two major goals: execution of DT ignition experiments starting in FY2010 with the goal of demonstrating ignition and a reliable, repeatable ignition platform by the conclusion of the NIC at the end of FY2012. The NIC will also develop the infrastructure and the processes required to operate NIF as a national user facility. The achievement of ignition at NIF will demonstrate the scientific feasibility of ICF and focus worldwide attention on laser fusion as a viable energy option. A laser fusion-based energy concept that builds on NIF, known as LIFE (Laser Inertial Fusion Energy), is currently under development. LIFE is inherently safe and can provide a global carbon-free energy generation solution in the 21st century. This paper describes recent progress on NIF, NIC, and the LIFE concept.

1. The National Ignition Facility

The National Ignition Facility (NIF) is the U.S. Department of Energy (DOE) and the National Nuclear Security Administration (NNSA) center to study inertial confinement fusion (ICF) and high energy density (HED) science. NIF is by far the largest scientific project ever successfully completed by the DOE. NIF, a cornerstone of the U.S. Stockpile Stewardship Program (SSP), will execute the science experiments necessary to ensure a safe, secure, and reliable nuclear weapon stockpile without underground testing. The 192-beam football-stadium sized NIF [1] is now operational at Lawrence Livermore National Laboratory (LLNL). A total 192-beam energy of 1.1 MJ 3 ω was demonstrated on March 10, 2009, over 30 times more energy than ever produced in an ICF laser system. Currently, the NIF is conducting experiments to commission the laser drive, the hohlraum and the capsule and to develop the infrastructure needed to begin the first ignition experiments in FY 2010. For example, 11 physics shots were performed in the period from August 16 to September 5, 2009. These shots used 192 beams of over 500 KJ and acquired excellent data.

NIF's 192 beams are directed into a 10-meter-diameter high-vacuum target chamber containing a ~1-cm-long cylindrical hohlraum target. The NIF target chamber contains entry ports for all the laser beams and over 100 ports for diagnostic instrumentation and target

insertion. Sophisticated diagnostic instruments such as x-ray and neutron spectrometers, microscopes, and streak cameras, can be mounted around the equator and at the poles of the target chamber. The laser interaction with the hohlraum will produce a radiation field with temperature of several hundreds eV. The resulting hohlraum conditions will provide the necessary environment to explore a wide range of HED science experiments, including laboratory-scale thermonuclear ignition and burn.

NIF is the most complex optical instrument ever constructed, with over 38,000 large and small optics and 60,000 points controlled by two million lines of software. The NIF 3 ω energy specification of 1.8 MJ requires an order of magnitude increase in operating fluence over previous laser systems. Developing high-quality optics that can withstand the NIF environment has been a major research and development focus at LLNL. A systematic and robust approach for optics finishing improvement and optics maintenance has been developed to support the ignition demanding requirements.

2.The National Ignition Campaign

2.1 Overview

The NIF ignition program is executed via the National Ignition Campaign (NIC) [2], a national effort that includes General Atomics (GA), LLNL, Los Alamos National Laboratory (LANL), Sandia National Laboratory (SNL), and the University of Rochester Laboratory for Laser Energetics (LLE). The NIC has two major goals: execution of deuterium-tritium (DT) ignition experiments starting in FY2010 with the goal of demonstrating ignition and a reliable, repeatable ignition platform at the completion of the NIC by the end of FY2012. The NIC will also develop the infrastructure and the processes required to operate NIF as a national user facility. The scope for NIC includes the ignition physics program as well as the development of the diagnostics, targets, target cryogenic system, phase plates and other optics, and personnel and environmental protection activities required to execute ignition experiments.

NIF ignition experiments will use a centimeter-scale hohlraum containing a millimeter-scale thin-walled plastic or beryllium capsule filled with a mix of deuterium and tritium. Compression of the capsule by the ~280-eV radiation field in the ignition hohlraum drives the DT fuel to conditions under which it will ignite and burn, liberating more energy than is required to initiate the fusion reaction [3]. NIF is designed to achieve target temperatures of 100 million K, radiation temperature over 3.5 million K, density of 1,000 g/cm³ and 100 billion times atmospheric pressure. These conditions have never been created in a laboratory and exist naturally only in the interiors of the stars and during thermonuclear burn.

Initial experiments aimed at understanding the energetics of the NIF ignition hohlraum and capsule-tuning experiments began in the summer of 2009. Cryogenic ignition targets filled with a deuterium-tritium mix capable of yields in the 10-20 MJ range will be tested in late FY2010. Experiments at other laser facilities such as OMEGA at LLE, Z at SNL, Trident at LANL and Jupiter at LLNL have been and continue to be used to develop and demonstrate tuning, shock timing, laser ablation and the diagnostics techniques needed to achieve ignition.

The NIC ignition campaigns uses the “indirect-drive” configuration, where the laser beams are directed into the ends of a cylinder coated with gold or other high-Z material mounted vertically within the target chamber. The laser irradiation of the cylinder produces a radiation field inside the cylinder that implodes a mm-scale capsule filled with a mix of deuterium and tritium. As shown in Figure 1, the laser beams are deployed in multiple cones so as to control the time-dependent symmetry of the radiation drive. The resulting asymmetry is maintained to less than 1% on average. The high degree of symmetry of the NIF implosion coupled with a precisely tailored target design and corresponding laser pulse results in the high peak fuel ρR required for alpha heating of the fuel and capsule ignition.

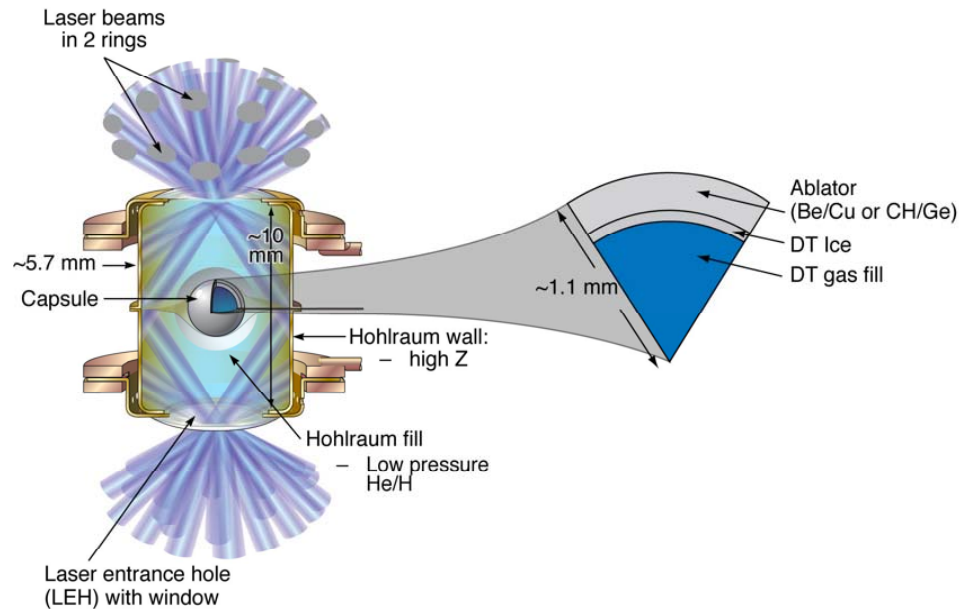


Figure 1. Schematic of NIF ignition target.

Initial ignition experiments will begin in late FY2010 at 192-beam ultraviolet laser energy of approximately 1.2 MJ. This energy level is consistent with the laser commissioning plan that ramps up to the planned 192-beam operating energy of 1.8 MJ by late 2011. The target design to be used is shown in Figure 1. Two capsule ablator materials (Be with Cu dopant and CH with Ge dopant) are currently under consideration. Both capsules are filled with DT gas via a 10-mm-diameter SiO_2 fill tube to a density of 0.3 mg/cm^3 with a DT solid layer at 18.3 degrees Kelvin. The Cu and Ge dopant density is varied through the ablator and is typically present at less than 1% concentration. Maintaining these two design options reduces risk and allows the choice of a target that is optimally configured to the precise laser and target fabrication capabilities available.

2.2 Ignition Target Developments and Fabrication

Ignition target development and fabrication has achieved considerable progress since the start of NIF construction in 1997; indeed, ignition target development and fabrication is a research and development program in its own right. NIC ignition targets must meet demanding specifications. Components must be machined to within an accuracy of $1 \text{ }\mu\text{m}$, with joints as small as 100 nm . The margin of error for target assembly is less than $8 \text{ }\mu\text{m}$. Typically, the

capsule outer surface must be smooth to within 1 nm, and the thickness and corresponding opacity of the doped layers must also be carefully controlled.

A long-standing challenge for ignition target fabrication is the frozen DT fuel layer [4]. This layer must be formed at approximately 1.5 degrees below the triple point of the DT mixture. The layer temperature must fluctuate no more than 1 mK, the roughness of the inner layer surface must be maintained at 1- μ m RMS roughness or better, and spherical isotherms must be maintained at the layer surface via auxiliary heating. These challenges have been addressed, and ignition targets meeting all specifications are now in production. Figure 2 shows an actual ignition target assembly featuring the thermo-mechanical package used to maintain the target at the required specification. The target is held at the center of the NIF target chamber via a cryostat attached to the NIF target positioner. The system also includes a characterization station capable of imaging the DT layer in three spatial dimensions within minutes.

2.3 NIC Diagnostics

The diagnostic suite for NIC is also a major focus of the NIC efforts in FY2009 and FY2010. By the end of FY2010, it is anticipated that approximately 35 diagnostics [5] measuring x-ray, neutron, charged particle, optical, and other emissions will be installed. Examples of diagnostics include full-aperture backscatter measurement capability for use in hohlraum energetics experiments, velocity interferometers for shock timing, absolutely calibrated soft x-ray spectrometers to measure the radiation drive, gamma-ray detectors to measure the burn history of the ignition target, and magnetic recoil spectrometers for neutron spectroscopy. Diagnostics development is a national and international effort. Further information regarding NIF diagnostics is available at the NIF website.*

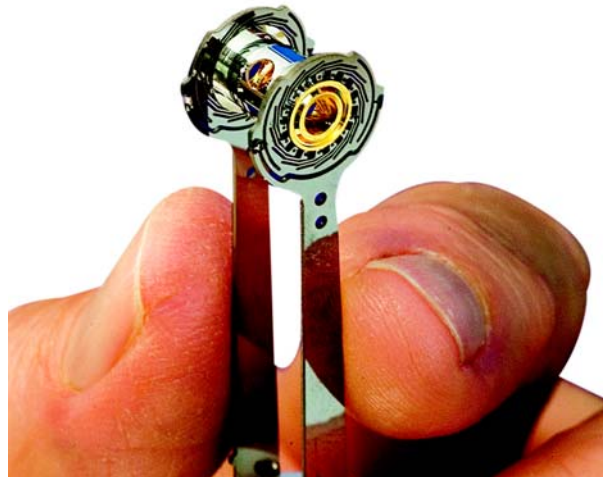


Figure 2. NIF fusion target thermo-mechanical package.

2.4 NIC Experimental Plan

The NIC experimental plan consists of four phases. The first phase will culminate with the first attempts at inertial fusion ignition in late FY2010. The subsequent three phases will

* NIF web site, <https://lasers.llnl.gov/programs/nic/diagnostics.php>

refine the target and laser parameters and investigate the physics of the ignition regime, with a goal of providing a reliable and repeatable ignition platform by the conclusion of NIC at the end of FY2012.

Based on many years of experimentation and simulations, it is believed that the NIC experimental campaign requires tuning 14 laser and 3 target parameters to those required for ignition conditions. The laser and target parameters to be tuned are shown in Figure 3. The tuning of these parameters corresponds to tailoring the capsule adiabat, velocity, symmetry, and degree of hydrodynamic instability. These 17 parameters are tuned in four steps designed to tailor the laser and cryogenic DT target to ignition conditions. In the first or “drive” step, the empty hohlraum is tuned to produce the necessary radiation drive on the capsule as a function of time. In the “tuning” step, a variety of non-cryogenic and cryogenic deuterium-filled capsules are used to adjust the hohlraum symmetry and shock timing so as to produce the compressed fuel central “hot spot” conditions required for ignition. The third step consists of layered cryogenic implosions conducted with a 50%/49%/1% mix of tritium, hydrogen, and deuterium (THD) respectively. The reduced yield from these THD targets allows the full diagnostic suite to be employed and the presence of the required temperature and fuel areal density to be verified. The final step is DT ignition implosions with expected gains of 10-20. The FY2010 DT ignition experiments will be conducted with $E_{\text{laser}} \sim 1.2$ MJ. Laser energies of 1.8 MJ should be available for subsequent experiments.

In preparing for executing the ignition experimental series, the NIC team conducted a “simulated campaign” to exercise the experimental team and develop the ability of NIC scientists to quickly tune the ignition target to the required conditions. The “Blue Team” specified and executed simulated experiments that exercised much of the NIF laser, target, and operational infrastructure, while the “Red Team” provided synthetic data that took into account specified target fabrication errors, laser power imbalance, backscatter, and cross-beam energy transfer. Over a several month period, the Blue Team demonstrated synthetic ignition by successfully adjusting laser and target parameters to compensate for detunings specified by the Red Team and reduced from days to hours the time required to examine a data set and experimentally tune the laser and target.

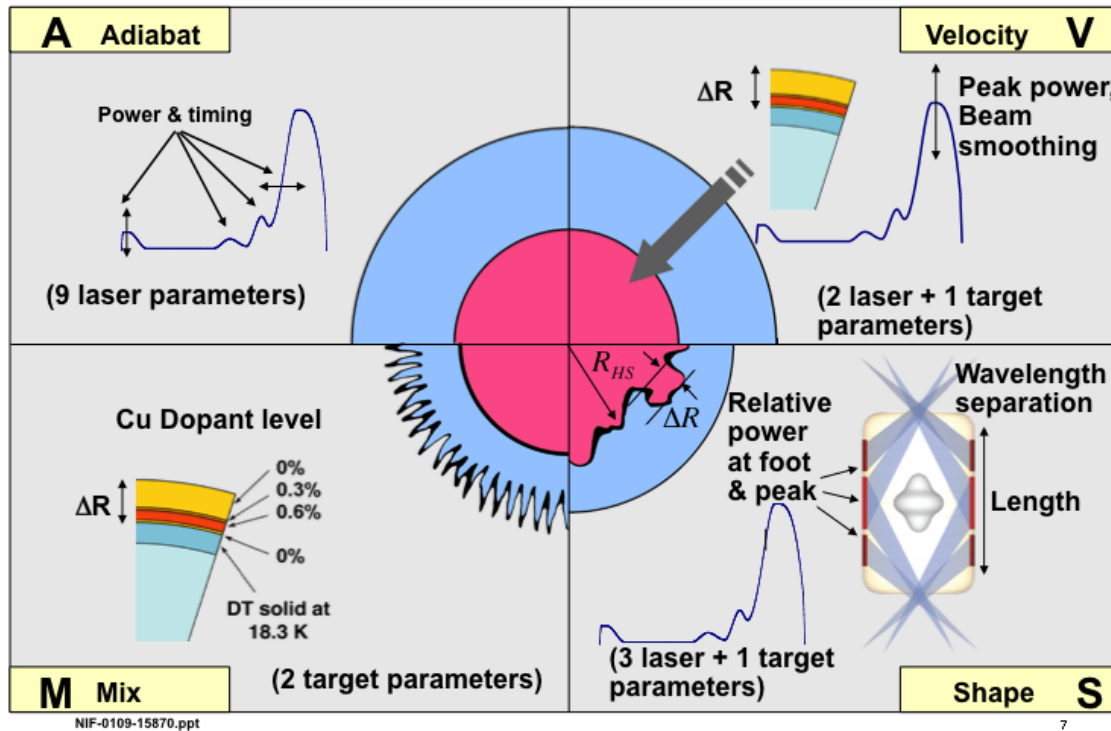


Figure 3. Laser and target parameters to be tuned in the NIF ignition campaigns.

3.0 NIF Multi-Mission Experimental Program

While the ignition experiments will be the primary focus through FY2012, NIF will execute other experiments in support of stockpile stewardship, national defense, and fundamental HED science. Weapons physics experiments conducted in this time frame will reduce uncertainties in key areas and enable improved predictive capability. Experiments conducted in collaboration with the Defense Threat Reduction Agency (DTRA) and the Missile Defense Agency (MDA) will validate NIF as an ultra-low debris soft x-ray ($E < 15$ keV) simulator. Nuclear survivability tests of specific components will also be conducted.

NIF will provide national and international researchers unparalleled opportunities to explore fundamental astrophysics, planetary physics, hydrodynamics, nonlinear optical physics, and materials science. Examples of experiments planned for NIF include investigation of the physics of planetary interiors, the formation of elements with $Z > 26$ via Type II supernovae explosions, excited state nuclear reactions, and ultra-intense laser-matter interactions. NIF will ultimately be a major international center for fundamental HED science.

4.0 Ignition and Inertial Fusion Energy

The demonstration of ignition at NIF will demonstrate the scientific feasibility of ICF and will likely focus the world's attention on the possibility of an ICF energy option. NIF will have a pulse repetition frequency of only 10^{-4} Hz and estimated electrical efficiency of 0.5%, while a 2000-MW Inertial Fusion Energy (IFE) power plant would require a repetition frequency of 5-10 Hz and 20% electrical efficiency, based on current expectations of achievable target gain. Fusion energy will thus require the development of lasers, chambers, optical

components, and other systems capable of operating at the ~ 10 Hz repetition rate required for hundreds of MW to a few GW fusion power plants. Considerable progress has been made on these technologies.

The achievement of ignition at NIF will motivate more detailed consideration of ICF as an option for clean, sustainable energy. Both pure fusion and fusion-fission hybrid schemes for energy production are under consideration. The key feature of this Laser Inertial Fusion Energy (LIFE) concept is the use of ICF-generated neutrons to induce fission reactions in the fuel, extracting virtually all its energy content and leaving only a small residue of long-lived actinide waste [6]. This approach could close the nuclear fuel cycle without the need for chemical separation and reprocessing, while generating thousands of megawatts of carbon-free electricity. Such scheme could also incinerate more than 99 percent of spent reactor fuel and extend the service life of deep geologic repositories by up to a factor of 20. The LIFE concept appears considerably attractive given the closed nature of the fuel cycle and the possibility of burning spent nuclear fuel and excess weapons plutonium and highly enriched uranium.

5.0 Conclusion

NIF is now operational, with ignition experiments expected to begin in late FY2010. After many years of R&D, most of the pieces needed for demonstrating ignition at NIF are in place, including the NIF laser, a detailed point design with adequate margin, high-quality targets meeting all specifications, and advanced diagnostics capable of precision tuning of capsule performance to ignition conditions. NIF is the centerpiece of the NIF experimental program. NIF ignition will allow access to the burning plasma regime for the first time, enabling important stockpile stewardship studies and demonstrating the scientific feasibility of ICF. More generally, NIF's ability to create extraordinarily high pressures, temperatures, and densities—as much as 1 trillion atmospheres pressure, 100 million degrees K temperature, and $1,000 \text{ g/cm}^3$ density—will enable major fundamental advances in support of DOE's national security, energy, and fundamental science missions. NIF and other major facilities worldwide will launch a new era in HED science and the demonstration of ignition may one day lead to an inexhaustible clean power supply for humanity.

Ignition at NIF will be a landmark scientific achievement and will open new possibilities for clean, sustainable energy production. NIF will also allow fundamental study of matter at extreme energy densities, including the possibility of examining astrophysical phenomena in the laboratory for the first time. NIF will open a truly new era in HED science.

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REFERENCES

- [1] Haynam, C A et al. 2007 National Ignition Facility Laser Performance Status *Applied Optics* **46** 3276
- [2] “National Ignition Campaign Execution Plan” 2005 LLNL report UCRL-AR-213718, NIF-0111975-AA
- [3] Lindl, J D 1998 Inertial confinement fusion: the quest for ignition and energy gain using indirect drive *American Institute of Physics Press* New York
- [4] Slater J, Kozioziemski B, Collins G W, Mapoles E R, Pipes J, Burmann J, Bernat T P 1999 Cryogenic D-T fuel layers formed in 1 mm spheres by beta-layering *Fusion Tech.* **35** 2 229–233
- [5] Moses E I 2008 Ignition on the National Ignition Facility: a path toward inertial fusion energy, *Nuclear Fusion*, to be published
- [6] Moses E I, Diaz de la Rubia T, Storm E, Latkowski J F, Farmer J C, Abbott R P, Kramer K J, Peterson P F, Shaw H F, and Lehman II R F 2009 A Sustainable Nuclear Fuel Cycle Based on Inertial Fusion Energy *Fusion Science and Technology* **56** 547